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on

INVESTIGATIONS OF THEORETICAL PROBLEMS IN COSMICAL GAS DYNAMICS

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Department of Astronomy and Astrophysics
University of Chicago
Chicago, Illinois 60637

Peter O. Vandervoort
Peter O. Vandervoort
Associate Professor of Astronomy
Principal Investigator

13

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This is the final report on investigations of theoretical problems in cosmical gas dynamics. An attempt has been made to derive a kinematical model of the Orion Nebula from observational models of the density distribution and data on the internal kinematics. Numerical methods have been developed for integrating the equations governing the dynamics of H II regions by the method of characteristics.

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ABSTRACT

This is the final report on investigations of theoretical problems in cosmical gas dynamics. An attempt has been made to derive a kinematical model of the Orion Nebula from observational models of the density distribution and data on the internal kinematics. Numerical methods have been developed for integrating the equations governing the dynamics of H II regions by the method of characteristics.

Introduction

This is a Final Report to the Office of the Naval Research on work performed under Grant NONR(G)-00005-66 (Task Number NR 046-794) to the University of Chicago. Period of the work was October 1, 1965 to December 31, 1970. Work was interrupted during 1967-68, when the Principal Investigator (Peter O. Vandervoort) was on leave from the University of Chicago, and during 1969, as a result of service by the Principal Investigator on a University Disciplinary Committee.

Grant personnel were:

Peter O. Vandervoort, Principal Investigator

Stuart L. Mufson, Research Assistant

The work performed is described in the following two sections.

THE EXPANSION OF THE ORION NEBULAE

This investigation was an attempt to construct a kinematical model of the Orion Nebula on the basis of 1) Spherically symmetric models of the distribution of the electron density derived from optical and radio observations (Osterbrock and Flather 1959; Menon 1961) and 2) observational data on the internal kinematics of the nebula (Wilson, Munch, Flather, and Coffeen 1959). The nebula was treated as an expanding, spherically-symmetric system in which random motions of the gas are superimposed on the velocity of expansion. Under such conditions, the average radical velocity $\langle V(s) \rangle$ of the gas observed in a given spectral line along a line of sight at a projected distance S from the center of the nebulae is related to the velocity of expansion $u(r)$, where r is the true distance from the center, in the manner

$$\langle V(s) \rangle = \frac{\int \epsilon(r)\, u(r) \cos\theta \; e^{-\tau}\, dl}{\int \epsilon(r)\, e^{-\tau}\, dl} . \qquad (1)$$

Here the integrations are performed along the line of sight through the nebulae, τ is the optical depth into the nebula, $\epsilon(r)$ is the volume emissivity in the spectral line, and the factor $\cos\theta$ projects the velocity of expansion onto the line of sight. Values of $\langle V(s) \rangle$ were derived from the catalogue of Wilson, et al., while values of $\epsilon(r)$ were derived from the papers of Osterbrock and Flather and of Menon. Optical depths into the nebula were derived from results of an investigation by O'Dell and Hubbard (19?5, private communication). The objective was then to find plausible functions $u(r)$ such that equation (1) would be satisfied over the range of s for which $\langle V(s) \rangle$ could be determined.

For the model envisaged, the expectation was that $u(r)$ should vanish at $r = 0$, increase to a maximum value u_0 (say) at some distance $r = r_1$ (say), and fall to zero as $r \to \infty$. Dynamical considerations imply that u_0 should be of the order of the isothermal speed of sound (about 10 km-sec^{-1}) at most. It was found that equation (1) could be satisfied only if $u(r)$ attains a maximum value of the order of several hundred kilometers per second. This result is unacceptable because it violates the aforementioned dynamical considerations and because it implies that the dispersion of the radial velocities in the nebula should be much larger than is observed.

When this result was obtained, it was recognized that one possible source of error in the analysis lay in the assumption that the Orion Nebula cluster is at rest relative to the center of the Nebula. On this basis, $\langle V(s) \rangle$ had been determined relative to the cluster. This procedure would give erroneous results for $u(r)$ if the nebula were drifting relative to the cluster. Subsequently studies of the radio recombination lines of hydrogen revealed such a drift (Mezger and Hoglund 1967). Departures from spherical symmetry must be additional sources of error. Indeed, more recent investigations (e.g. Webster and Altenhoff 1970) now indicate that the Orion Nebula is much less regular and symmetric than was believed when this work was undertaken. For these reasons, it now appears that a reliable kinematical model cannot be derived along these lines.

NUMERICAL METHODS FOR THE INVESTIGATION OF THE EVOLUTION OF H II REGIONS

It had been proposed under this Grant to investigate aspects of the early evolution of an H II region which had become of interest in earlier work (Vandervoort 1966). In particular, it was intended to consider further the effects of the finite time scale for the formation of the exciting star and to include a more careful treatment of the ionization and heating of the gas in the formulation of the dynamics of the H II region. A central question was whether the early evolution of an H II region would be characterized by an ionization front of the R-type propagating directly into the undisturbed neutral gas or a front of the D-type following a shock into the undisturbed gas. And if the front were of the D-type, the question arose whether or not a rapid increase of the luminosity of the exciting star would induce a transition to a front of the R-type. This question had been raised earlier in an investigation of non-stationary ionization fronts (Vandervoort 1965 a,b).

It was clear at an early stage of the work that the development and use of numerical methods would be required. Accordingly, the thrust of the work shifted to the development of suitable numerical schemes for integrating the basic equations. At the time this work was undertaken, other investigators, particularly Mathews (1965) and Lasker (1966), had investigated the evolution of H II regions by numerical integration of the hydrodynamic equations in a Lagrangian representation. It was thought that the present work might compliment those investigations if it were based on other numerical schemes. For this reason and because the Principal Investigator had had previous experience in the use of the method of characteristics (Courant and Friedrichs 1949), it was decided to develop numerical methods for integrating the basic equations by the method of characteristics.

In particular, such a scheme has been developed for the numerical integration of the equations governing the structure of a non-stationary ionization front (Vandervoort 1965a; all equation numbers in this section of this report refer to equations in that paper). Characteristic equations corresponding to equations (1), (2), (4), and (6) were derived in a conventional manner (Courant and Friedrichs 1949). These were replaced with a system of finite difference equations appropriate for a numerical integration by a "method of specified time intervals" (Lister 1960). At each time step in the integration, the flux must be determined by integrating equation (3); this was accomplished with the aid of a conventional scheme for numerical quadrature. The boundary conditions expressed by equations (8) - (10) were replaced with boundary conditions at the first and last points on the spatial grid.

A program for the execution of this method has been written, and it has been tested on the problem of a stationary ionization front for which an exact solution is known (see §IV in Vandervoort 1965a). Considerable experimentation was required to find satisfactory combinations of the number of points in the spatial grid and the size of the time step. The status of the work at the end of the grant period is that it has been possible to produce accurate solutions for the structures of stationary R-type fronts for intervals of time greater than the characteristic time scales during which elements of the neutral gas are over-run and completely ionized. These results encourage the belief that with further development these methods could be applied to non-stationary fronts and generalized for application to other aspects of the dynamics of H II regions. In view of the circumstance that such work would involve a considerable investment of computer time, for which funds are currently unavailable, work on this project was suspended at the end of the grant period.

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